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IRRIGATION WELLS AND WELL-DRILLING METHODS IN CALIFORNIA

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THE FOLLOWING discussion is offered, not to provide a manual for well-drillers, but to acquaint farmers with the operations involved. In addition, well characteristics are considered so as to aid irrigators in understanding the behavior of their wells. In certain areas, only one type of drilling equipment is represented, whereas in others, several types are operating. It is not always economical to bring a particular kind of drilling rig to a territory that does not have one; to move these heavy outfits is expensive. For this reason, the desirable features of a particular method may not be available to an owner. Arrangements can usually, however, be made to complete the proposed well satisfactorily with the equipment available. By studying these pages, potential well-owners may perhaps be helped toward reasonable decisions regarding the location, drilling, development, and use of this relatively expensive asset to their property.

The practices of irrigation-well drilling and development are already established in California, where about two-fifths of the irrigated land (fig. 1) is supplied from wells. Early development in the late nineteenth century was largely confined to the use of shallow water supplies that could be reached by hand-dug pits or wells and which could in turn be harnessed to the crude pumps and engines then available.

Though the underground waters of the state have been utilized for over half a century, there is still lack of understanding as to their source of supply and the best methods of obtaining and using them.

SOURCES OF UNDERGROUND WATER

Fundamentally, all underground water comes from precipitation, as does also the surface water. As is adequately demonstrated from records of precipitation and stream runoff, not all the water that falls appears as streamflow. Instead (fig. 2), some of it is intercepted by the vegetation and is evaporated back to the atmosphere, never reaching the ground. A portion that does strike the surface seeps or percolates into the earth at or near the point of contact. Some of this moisture is taken up by the roots of the vegetative cover, some

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evaporates from the soil surface, and the rest is stored in the soil (fig. 2). Because these processes of precipitation, runoff, percolation, vegetational use, and storage have continued for millions of years, a balance was reached long ago; the moisture in the soil at lower depths has reached a limit beyond which

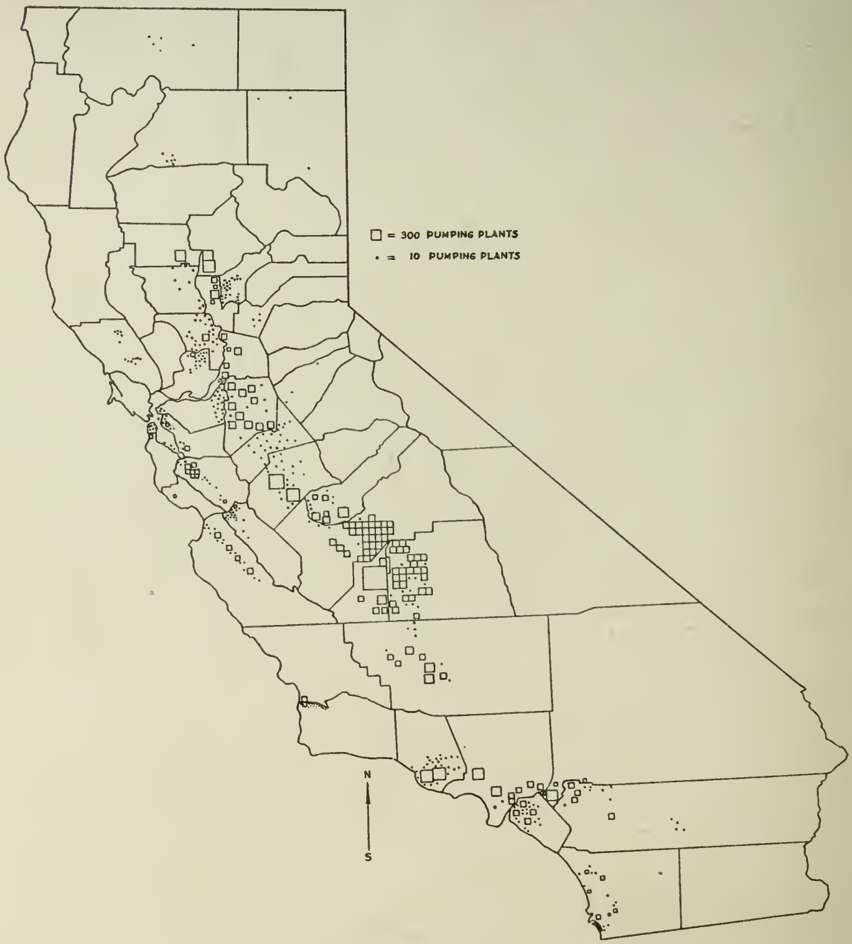

Fig. 1.—Map of California, showing concentration of irrigation pumping plants in valley areas.

no more storage can be accommodated. When this condition prevails, any surplus water tends to flow through the soil mass. The downward pull of gravity on this water is often blocked by underground rocky formations or by other dense layers such as clays or hardpans; and vertical progress is restricted to a combination of horizontal and downward movement, or to a sloped plane. The active moving force is still the gravitational pull, which is vertical; but the water, adapting itself to the easiest paths of escape under this force, moves horizontally or even upward at times if the source of flow is sufficiently high.

DISTRIBUTION OF UNDERGROUND WATER

Fortunately for California, her land masses are so arranged that large agricultural valleys lie between extensive mountain ranges. Thousands of years ago the mountains were higher and the valleys lower. Through the centuries, precipitation has found its way from mountain to valley. Weathering in the mountain masses has produced broken fragments of rock in varying

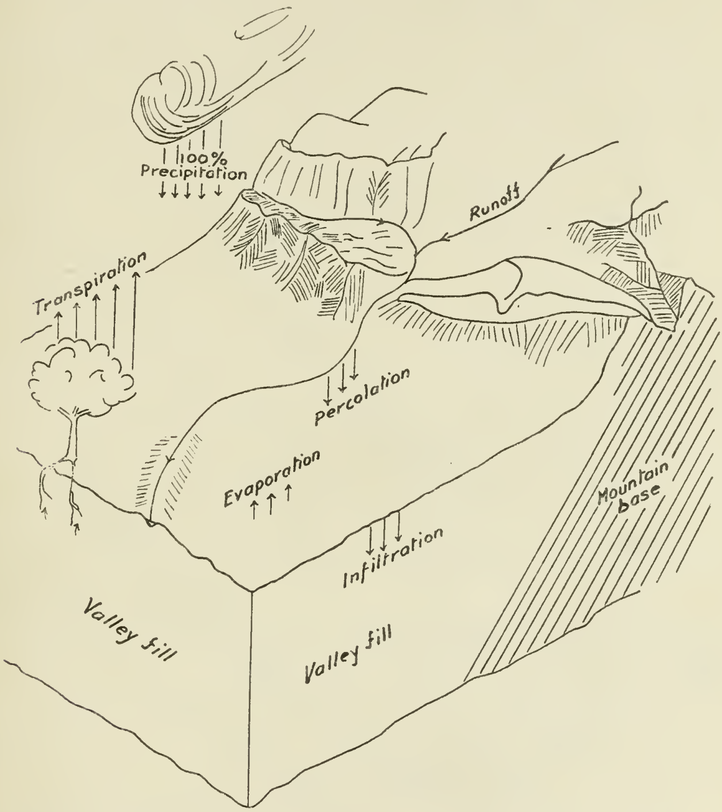

Fig. 2.—Section of valley with mountains in background, showing disposal of precipitation.

sizes, and the streams have borne this weathered material both under normal flow and during the tremendous floods of ages past. In the process, these rock chunks were ground upon each other, their sharp edges were rounded, and smaller particles were formed. Since the grinding continued as long as the weathered rock remained in the streams, the result was material ranging from coarse to fine.

At first the streams had more slope than at present; they swept out from the mountain flanks at greater velocities and could transport the coarse fragments farther out on the valley floors than today. As they continued to dump these burdens, their beds lost slope, and their flow velocities were reduced. Because material therefore fell out of the streams sooner, the beds filled until they

became higher than the surrounding territory. Floods cut the banks, and new channels were formed, only to be choked in turn; new breaks occurred in the banks, and the streams were made to wander across the detritus fan.

The resultant areas constitute our present valley fills. Over these are flowing the descendants of the early streams. Some still leave their banks at flood

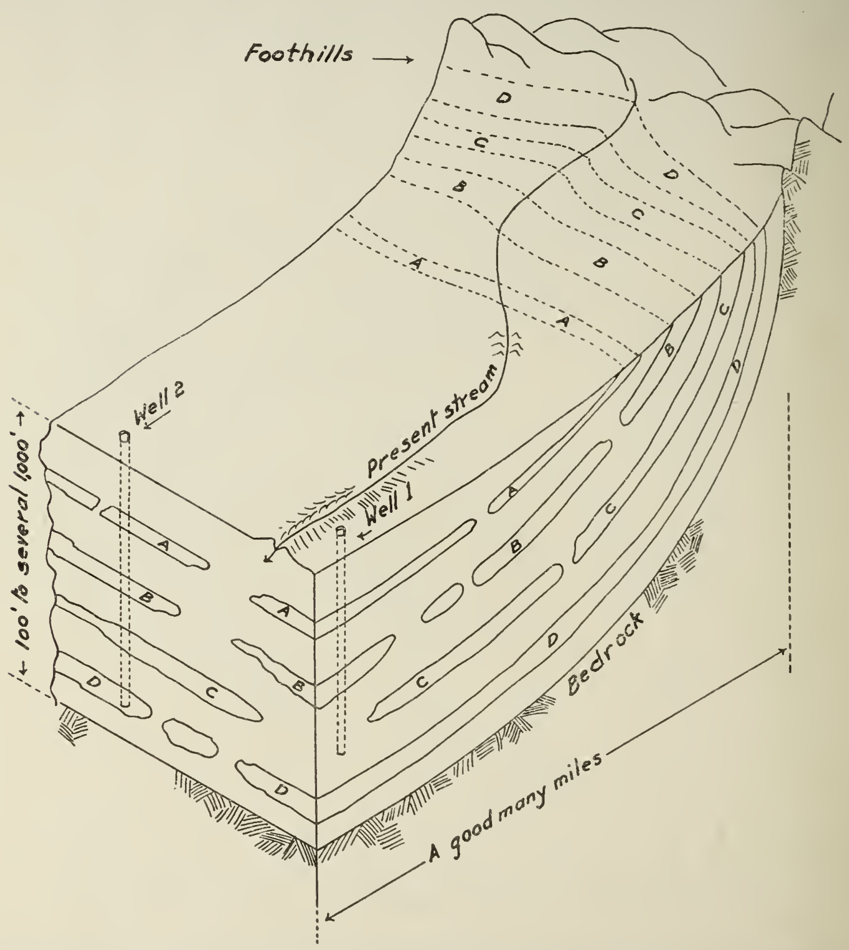

Fig. 3.—Cross section of valley fill, with detail of strata from soil surface to bedrock.

stage and continue to form depositional slopes, deltas, or alluvial fans. The material dropped was at first the coarsest rock, then finer and finer material, till the finest particles that make up our present sedimentary clays settled out in still water. This deposition, taking place along the downward course of the streams, made sloping sheets of varied texture, layer upon layer (fig. 3). The early layers, having the greatest slope, intersect more recent ones; and so on to the top of each fill. As a result, the valley floors are composed of alternate layers of various material depending upon the conditions that prevailed when each layer was deposited. These layers have been cut and scoured by

the wandering stream beds so they are not always unbroken planes, but more frequently form strips or bands or lenses of the original material. Toward the center of the valleys farthest from the mountains, deep gravels connect with the shallower gravels nearer the sides of the valleys; and so on toward the present mountain ranges, where great gravel banks still attest to the magnitude of former floods and the sweeping transportational operations of streams in the past.

Present Value of These Old Stream Channels.—Because the valley floors in California have been formed in the manner just outlined, the modern driller can sink wells through these layered materials in the valleys with some hope of finding strata that contain an effective supply of water for irrigation. The water-bearing strata encountered are usually portions of a large sloped sheet of that same type of material, with the upper ends of the slope crossed near the mountain flanks by the present streams. These streams, percolating in passing, replenish the water-bearing strata more or less completely after each year's pumping season. Additional water reaches these layers by gradual infiltration from the valley surface.

Water-bearing Materials.—In the search for strata containing a water supply, one may safely assume that not all these materials are effective sources. The reasons are numerous. To be effective, a stratum must transmit or carry water within itself rather easily. In other words, if supplies cannot move through it to a well fast enough to replace the water being taken out, the well will run dry. Water will pass through porous materials. Clean gravels and coarse sands, with comparatively large pore spaces between adjoining particles, are therefore the water-producing strata in our wells; although the fine sands and the clays may have just as much pore space, the pores are smaller because the particles are finer. Water cannot pass through the small pores so easily as through large ones.

In drilling for water, the hope is that the drill will intersect a good proportion of gravel and coarse-sand layers. Sometimes, however, a large amount of these materials may occur in a well and yet be unproductive, or almost so: the strata drilled may be isolated from the rest of the valley fill by layers of clay laid down by the prehistoric wandering streams. Fortunately, this situation is not normal in California valleys, so that most of the potential water-producing strata are actually usable.

Water Levels in Wells.—The water in a productive stratum has arrived there from some higher point by moving through the transmitting layers and through the stratum itself. If the stratum has been filled so most of the water can escape and if a well is put down, the water will rise no higher than the source of supply. If the source is above the well, the water may flow from the top of the casing; such a well is called flowing artesian. If the source is somewhat lower than the top of the casing, or if the water comes up part way in the casing above the supplying stratum, the well is nonflowing artesian. Wells in which the water fails to rise above the supplying strata are nonartesian. When an artesian well flows or is pumped, water movement takes place in the supplying strata. This movement encounters resistance, or friction; and consequently there is less pressure, or head, at the well than before flow started. As a result, the flow diminishes, or the water levels in the pumped

well drop. Other nearby wells, if connected with this same stratum, feel in turn the effect of flow within the stratum caused by the first well, and their pressures also are lowered in time. This lowering is noted as the seasonal drawdown in pumped areas from spring to fall.

The recovery of water levels in winter indicates that infiltration to the conducting strata has replenished the water used and that pressure under the area has been restored. If the levels in wells do not recover from spring to spring, the infiltering supply is inadequate; and unless this lowering process stops, the available supply to the area may be seriously depleted. Often, in an area, the seasonal recovery is less than the seasonal drawdown in the wells for several years, after which the two reach a balance. Under these conditions, the lowering of water levels represents the reduction of pressure necessary at the wells to permit the required flow from the source through the supply strata. In other words, some recession in general levels is necessary in order that the water needed may move toward the area of use. In moving, it encounters resistance; flow is impossible unless it can pass toward a zone of lower level or lowered pressure.

In areas where the seasonal recession is unabated, there must be some means of replenishing the underground supply. The job of replenishment for an area can be attempted only with the coöperation (especially financial) of all who will benefit. It may require the storage of water behind expensive dams, the construction of canals and ditches, and the operation and control of percolating areas. Since these works require a large investment, they should be undertaken only with sound engineering advice and planning. Storage would be in the upper drainage basin, and the percolation areas would be in the present stream bed and on prehistoric beds represented by the gravel bluffs and terraces that fan out now on the foothills at the point where the present streams enter the valleys. From certain areas of the state come reports[2] on the procedure in organizing, designing, and constructing such underground water-replenishment systems.

DRILLING METHODS IN CALIFORNIA

Because the water-bearing strata in the valleys are a considerable distance below the surface proper, manual excavation is laborious. In many areas the difficulty for the hand-constructed wells has been increased by the lowering of levels necessary to permit flow from the source. This lowering makes hand-digging extremely dangerous as well as difficult. To eliminate the hazards and to ease the burden on men, power-driven equipment has been developed. These mechanized devices have replaced the manual drilling of irrigation wells in California except for occasional small-bore shallow developments for windmill or similar small-capacity pump use.

The three principal types of well drilling are excavation, cable, and boring. A fourth type, but of minor importance, is jetting.

Excavation.—As its name implies, excavation is the development of a hole,

[2] As an example of progress made in planning water-replenishment systems, there might be cited the report made by Mr. Fred H. Tibbetts to the board of directors of the Santa Clara Valley Water Conservation District on the 1934 well-replacement project. This report outlined the physical aspects of a typical valley and recommended a procedure for the organization and construction of a water-replacement system.

usually rather large, by use of hand shovels or power-driven shovels of various design. This, the oldest method, has not changed fundamentally in the hand-operated phases since Bible times, when Joseph's well was excavated. In those days one man started to dig, throwing out the dirt till the hole became too deep. Then a second man, standing part way down, relayed the dirt to the top; and so on as they went deeper. Sometimes a bucket or basket replaced

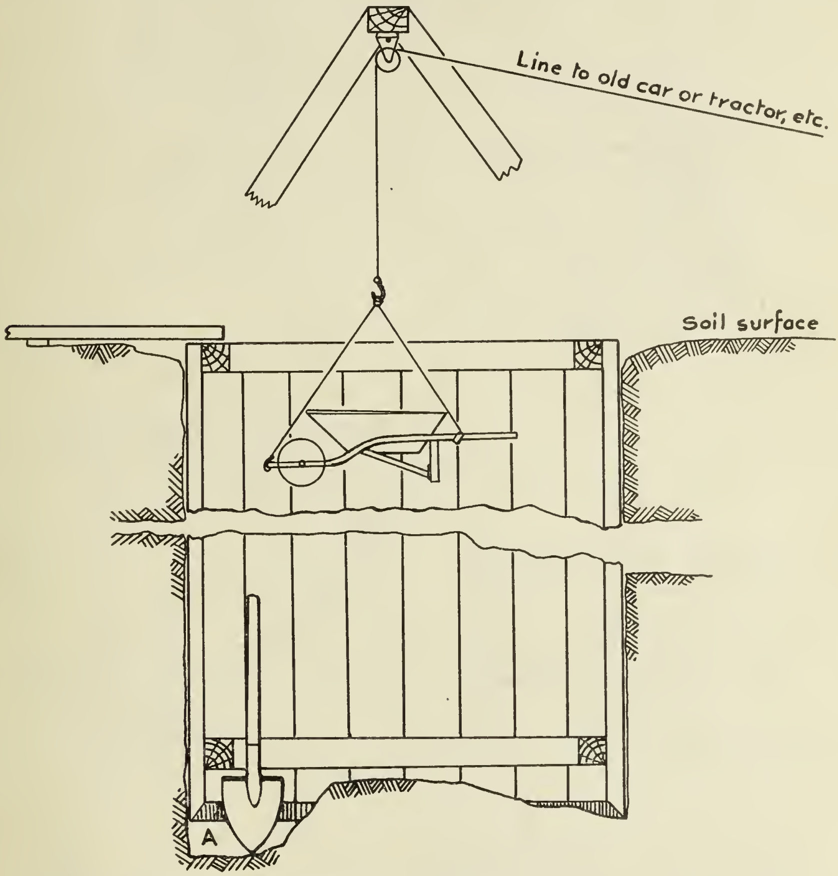

Fig. 4.—Partially mechanized excavated well with wood cribbing. The earth at *A* has been excavated below the edge of the cribbing.

the chain of men, and often many diggers worked together on the floor of large holes that became community or municipal wells. Today man supplements his efforts with mechanical devices, often lifting the spaded material from the bottom with power from a tractor or an old automobile, by use of suitable pulleys and lines (fig. 4) upon which is hung a container such as a wheelbarrow.

Safety requires that a carefully made continuous lining or cribbing be lowered as the hole deepens. This is particularly true in the unconsolidated sedimentary material normal for California valley floors. Unless such pre-

cautions are taken, the digger's life may be forfeited by a cave-in occurring at any depth more than 3 or 4 feet from the surface. The hazard increases with the depth; the cribbing must follow the excavation, leaving just enough space to permit trimming of the vertical earth walls so the cribbing can pass

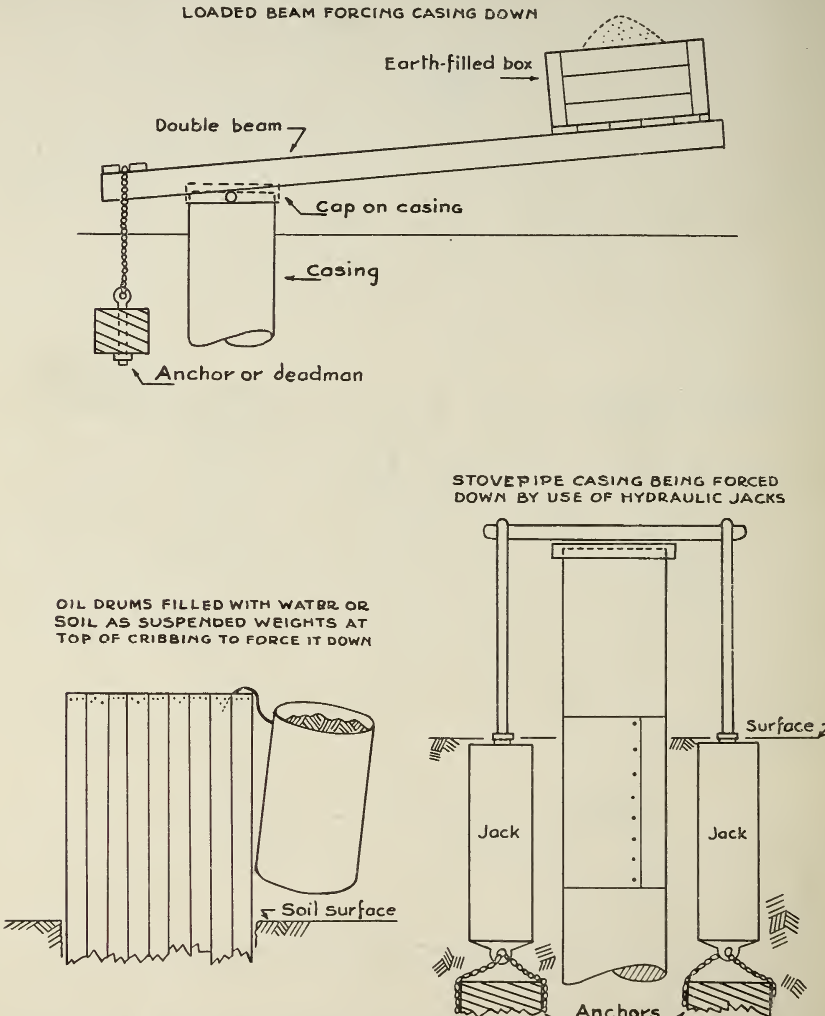

Fig. 5.—Various methods used to force casing and cribbing downward.

downward. Cribbing may bind on the sides of the hole because of slight caving or for other reasons, in which case its top can be weighted to force it down (fig. 5). Water or earth in suitable containers devised on the job make simple weighting materials to force the cribbing downward. The cribbing for the sides of the hole is necessary to hold back caving formations. To mechanize the excavation method requires clam-shell or orange-peel type buckets (fig. 6), which both dig and remove the material. These buckets can excavate under

water, unassisted, as long as the cribbing prevents a cave-in. If water is encountered, hand-excavated pits must be kept relatively dry by pumping—another complication, which generally limits the penetration of hand-dug wells into watered zones to approximately 6 to 10 feet.

In a few instances, drillers have made large excavations into water-bearing

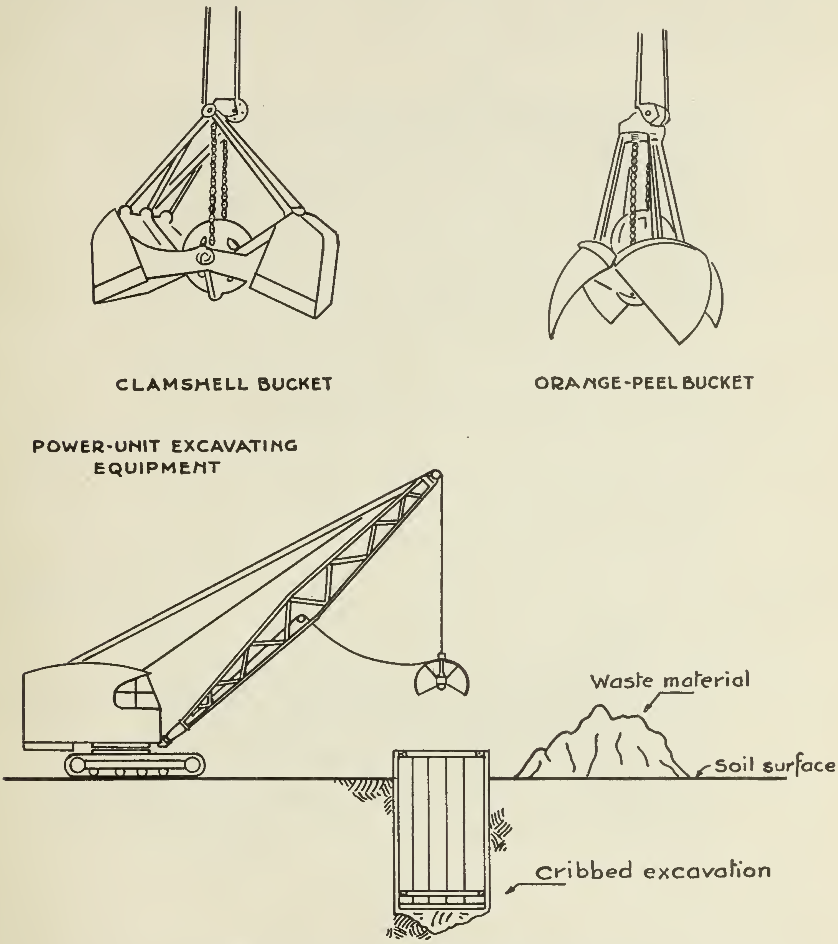

Fig. 6.—Power equipment for excavating.

gravels from the surface (fig. 7), leaving an open cut (sloping banks) filled with water at the bottom. Since the inward motion of the water to the cut resulting from pumping disturbs the bottom and banks, the pump foundation shifts, and it is therefore difficult to set pumping equipment near the water. An alternative to the open cut is to open it at first, install porous casing along the bottom, and then refill the pit, placing coarse clean gravel along the porous casing. The pump may then be connected to the porous casing with satisfactory results. The cribbing and casing mentioned above will be discussed under well casing.

Cable Equipment.—This type covers a group of devices suspended from a cable, whose vertical motion causes the tools to surge up and down in the hole, breaking the formation at the bottom so that other cable tools (or sometimes the same ones) can remove the loosened material. Under this type is grouped a large family of equipment having varying usefulness (fig. 8). Cable tools (fig. 9) differ radically from the cable-suspended orange-peel

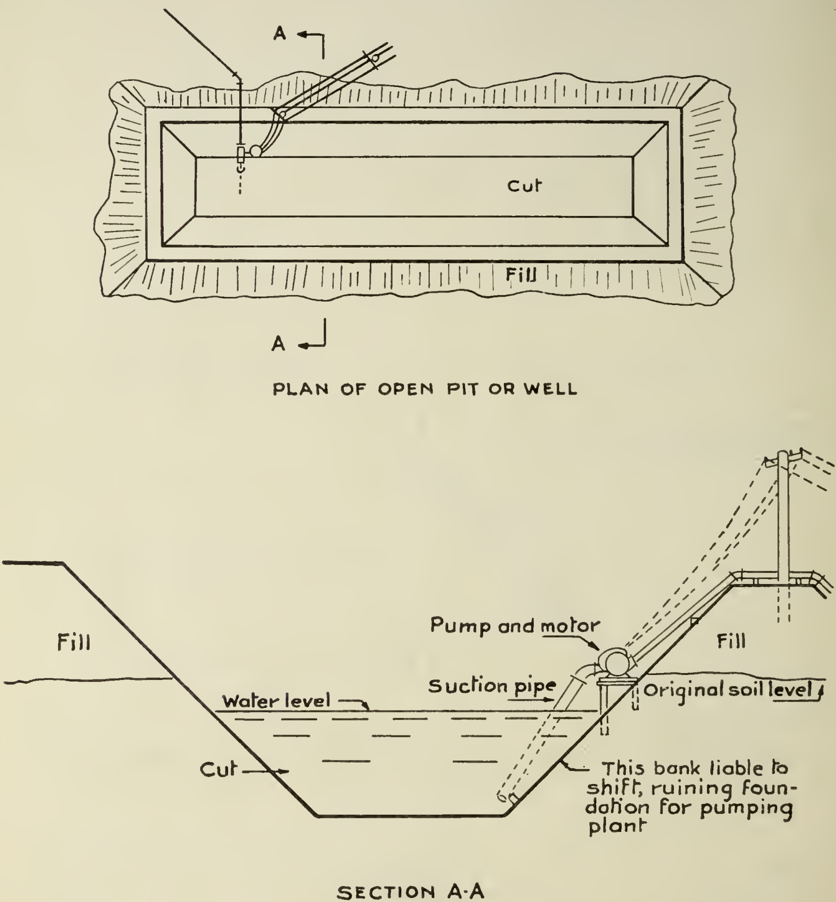

Fig. 7.—Plan and section of open-cut well with pumping unit installed.

and clam-shell buckets used in excavated wells: instead of gouging out chunks of material, they loosen, soften, and entrap. Most of them work best in water, which promotes the softening and suspends the loosened material for entrapment in the body of certain tools. The loosening and softening results from the pounding at the bottom of the hole.

In friable material, tools of the bailer class (fig. 9) are used both to loosen and to entrap the solids being cut. The resultant loosening combines surge action with some cutting by the bottom edges of the bailer or scow. The material thus loosened is suspended in the water in the hole, and the valve

at the bottom of the tool admits this mixture as the tool sinks farther. When the tool is full, the cable is reeled in, and the entrapped debris is dumped. In hard, compacted substrata and in rocks, the bailer-type tool will not act rapidly, and heavier bits of the flat or star section are therefore suspended on the cable (fig. 9). These bits batter the resisting material to small fragments. A scow or bailer must be lowered into the hole, replacing the bit and removing the cuttings. Where there is danger of the bit's jamming, and

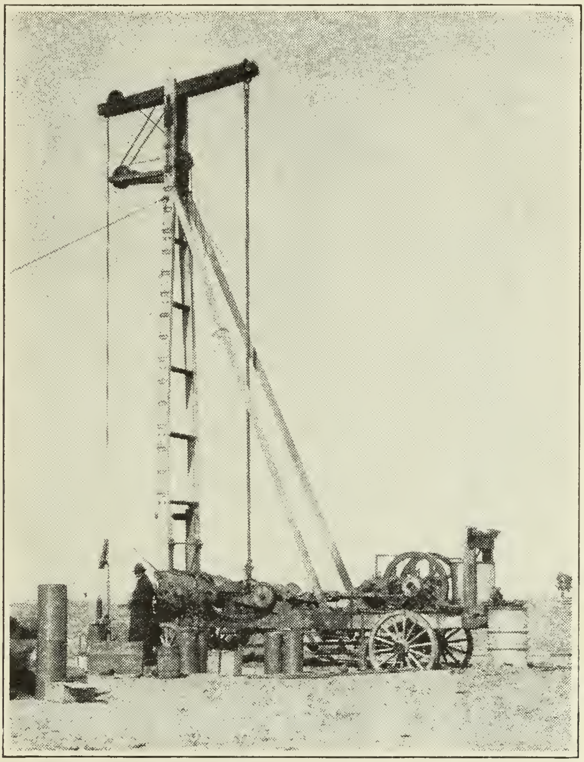

Fig. 8.—Cable-tool drilling rig. Stovepipe casing sections in left foreground.

where an additional weight will be more effective than the bit alone, heavy rods (called jars) with a sliding yoke section are fitted above the bit. The sliding yoke permits a hammering blow from above on top of the rigid lower section and also an upward blow if the bit itself is stuck.

The remaining tools supplement those mentioned. The swage, for example, forces out the walls of a collapsed casing. Tapered and smooth, it will true up a collapsed section so the other tools can pass. Operating trouble often means a broken cable, with loss of tools at the bottom of the hole. Although each operator has his own devices for fishing out lost tools, there are few standard pieces of equipment for the purpose. Drillers do, however, perform marvelous feats in recovering tools.

In general, cable tools require a water supply at the well site during oper-

ations and are limited to the making of holes less than 14 to 16 inches in diameter. Because drilling proceeds through the casing, comparatively accurate samples of the material being cut are dumped regularly at the surface; the depths and structure can be accurately noted. Such a record is

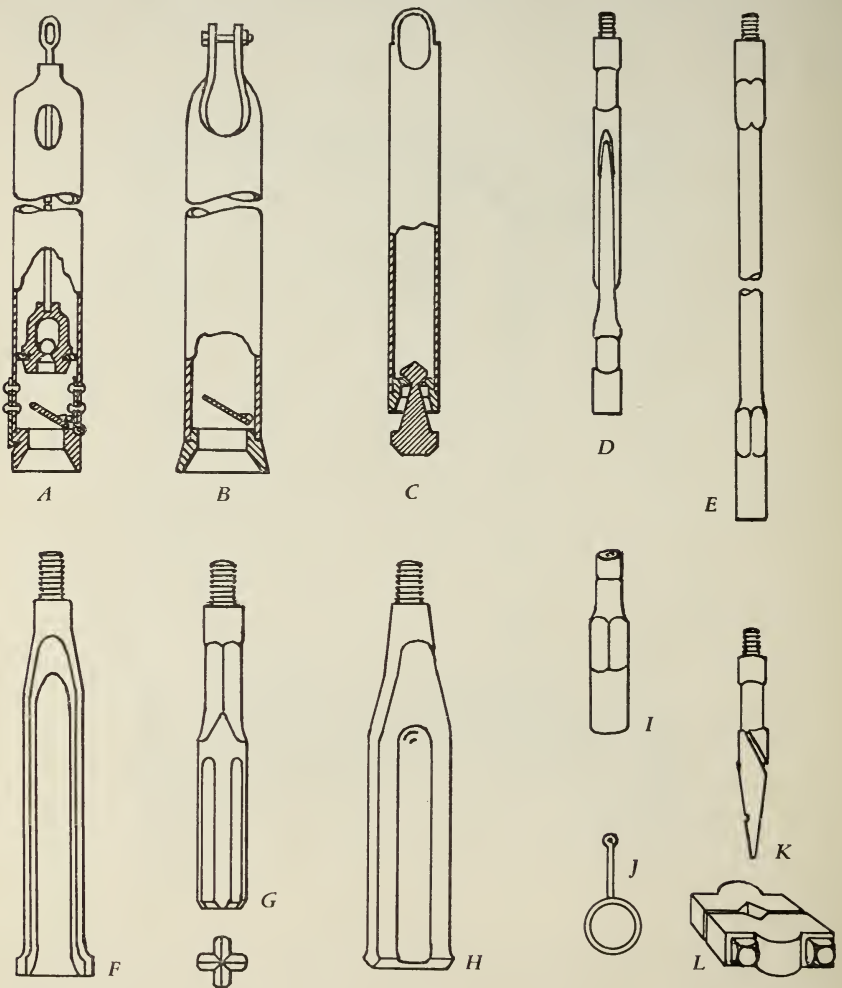

Fig. 9.—Cable tools: *A*, suction or sand bucket; *B*, scow or bailer; *C*, dart-valve bailer; *D*, jars; *E*, drill stem; *F*, standard bit; *G*, star bit; *H*, heavy-duty bit (spudder type); *I*, rope-sub; *J*, bit gauge; *K*, swage; *L*, drive clamps.

necessary when the time comes to perforate the casing opposite the potential water-producing strata. Perforating methods will be discussed under well casing.

Boring.—This method involves equipment that is turned from the surface by use of a drilling column. The cutting faces are in tools located at the bottom of the column; according to the device in use, they may or may not need to be removed to bring the cuttings up from the bottom of the hole.

Bored wells may be classified under two procedures. In the first, the boring tool works best in cohesive materials, such as clays, and requires no water to function most efficiently. This tool has an augerlike blade at the bottom. When the drilling shaft is turned at the top, the cutting faces of the auger

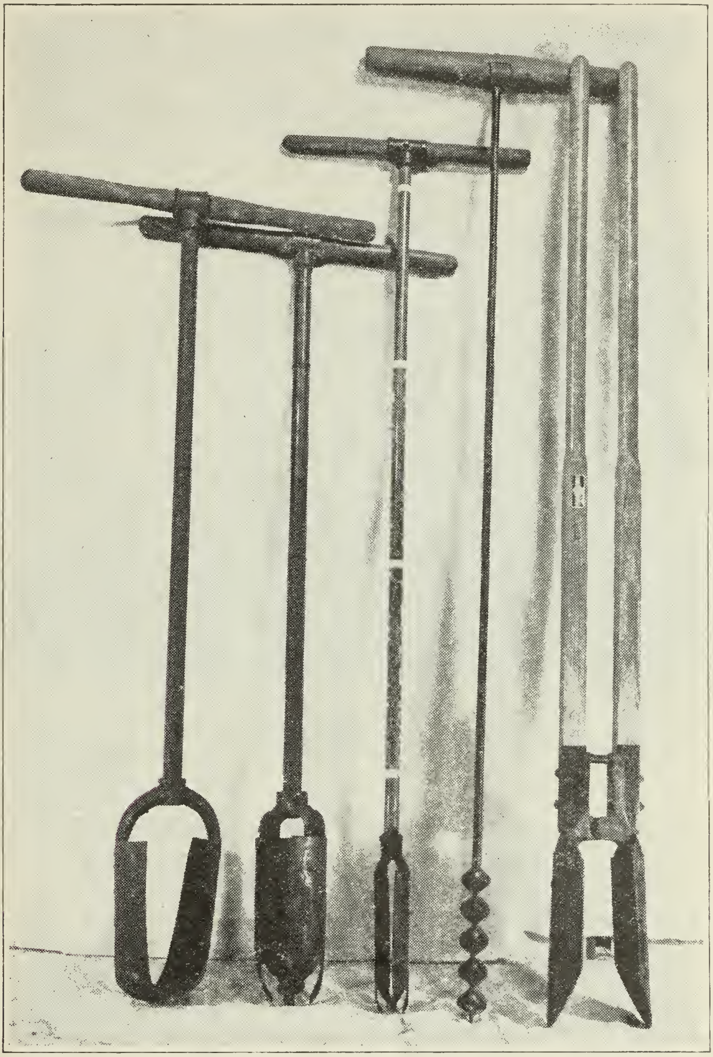

Fig. 10.—Hand-operated augers and excavators. Left to right: three post-hole augers, sizes 6-inch, 4-inch, and 2-inch; carpenter's bit-type auger; clamp-type post-hole digger (useful only to shallow depths).

peel the soil from the hole, discharging it into the cylindrical chamber above the bit surfaces. The cuttings thus collected are removed by retraction of the tool, which involves the dismantling of all drill shafting each time. This tool fails if it encounters loose gravel or sand, or if water enters the hole, sluicing the cuttings out of the container when the tool is elevated from the bottom.

Its chief use is to supplement the cable tool when sticky resisting materials can be cut more speedily by the auger-shaped bit than by the churning cable tools. The hand-sized models of these augers (fig. 10), typified by some post-hole diggers, are occasionally used in sinking small-diameter wells 50 to 100 feet. As has been noted, the power-driven tools (fig. 11) are limited in their application to the cutting of certain materials.

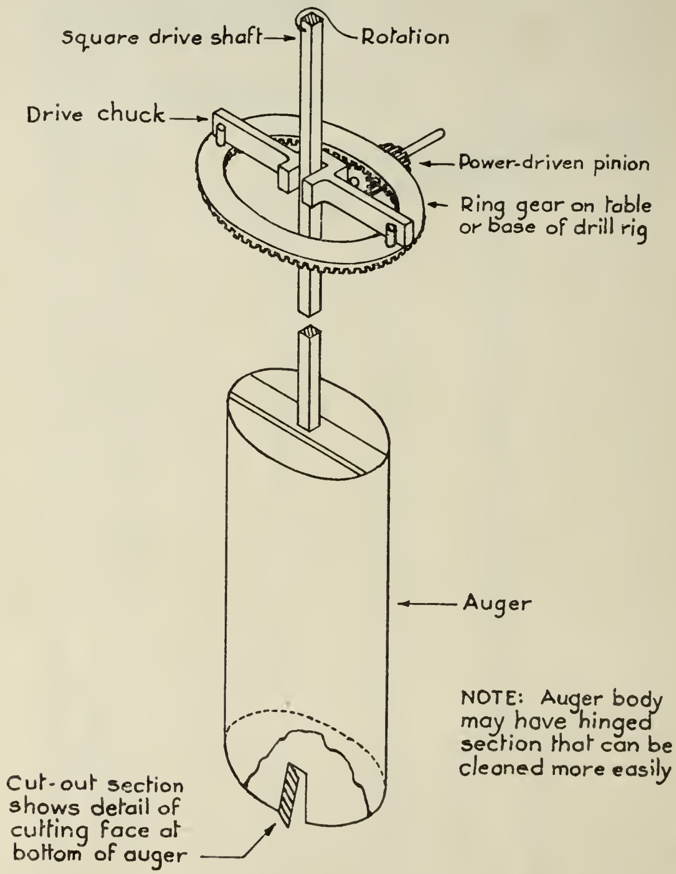

Fig. 11.—Power-driven auger, with portion of driving mechanism.

The other type of boring equipment is the so-called rotary rig (fig. 12). In such drilling, a water supply must be provided as soon as the well is started; the tool operates efficiently only in a thick muddy suspension, of its own stirring, called rotary mud. The cuttings from the hole are removed by pumping this muddy mixture down the hollow drill shaft to the sides of the bit (fig. 13), whence it travels upward outside the shaft, bearing the loosened materials to the top (partly floating, partly washing). If the rotary mud is not thick, it will not be heavy enough to float the cuttings; a good, creamy suspension must be maintained. Since this mud-filled hole stands up securely

while the whole well is dug, no casing is involved in the drilling proper. The mud not only elevates the cuttings while holding up the sides, but seals off the water-bearing loose gravels and sands so that they do not slide into the open hole.

Usually a pilot hole of small diameter (8 to 10 inches) is put down first. This prospects the zone below the surface, locates the potential water-bearing strata, and provides a well log on the spot from which the final depth of the well can be decided, as well as the location of the perforations. This pilot hole, if found potentially unproductive, is not costly; the driller can move to some other site at once, perhaps at a considerable saving to the owner. The com-

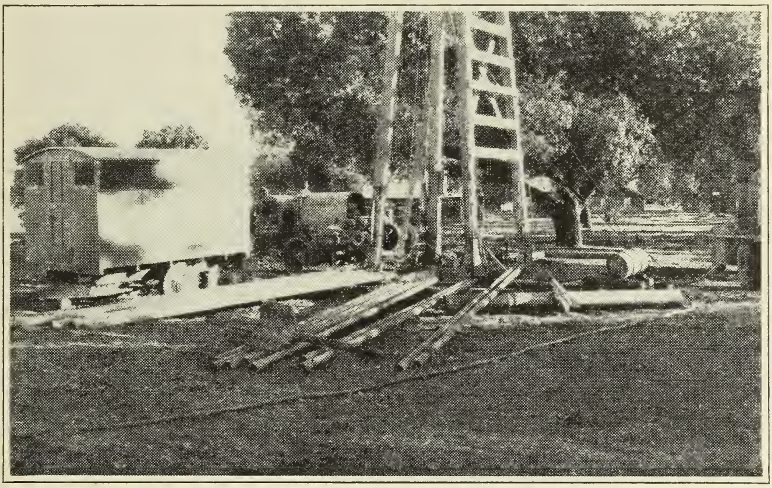

Fig. 12.—Rotary-drilling rig. Reamer in center foreground; bit to right of rig in foreground; seven drilling pipes or drill stems under reamer; bailer under bit; truck, at extreme right, to haul water for mixing into rotary-mud stream.

pleted hole follows the test hole as a guide, and the enlargement results from the action of reaming blades attached to the side of the drill tool just above the bit (fig. 13). These blades can be adjusted by bolting on to the wings above the bit. Like all cutting tools, they tend to wear; they are resurfaced frequently by the welding of hard metals on the cutting edges. If they are not kept sharp and to size, their efficiency suffers.

The final hole is usually 6 to 12 inches greater in diameter than the casing to be put into the well. After the casing is placed, the excess bore is filled with coarse, clean, uniform-sized gravel that acts as a continuous porous screen between the hole proper and the casing. This gravel is not admitted into the well until the driller has thinned the rotary mud markedly by pumping clear water to the bottom of the hole and washing the excess mud out of the top. At this time sufficient gravel must be available to fill the space outside the casing; the mud, when thinned, is not heavy enough to hold up the walls of the well for any considerable period. In addition, the gravel is carefully introduced so that the casing will not be forced sideways. Since wells of this type sometimes continue to take gravel for several months or a year after

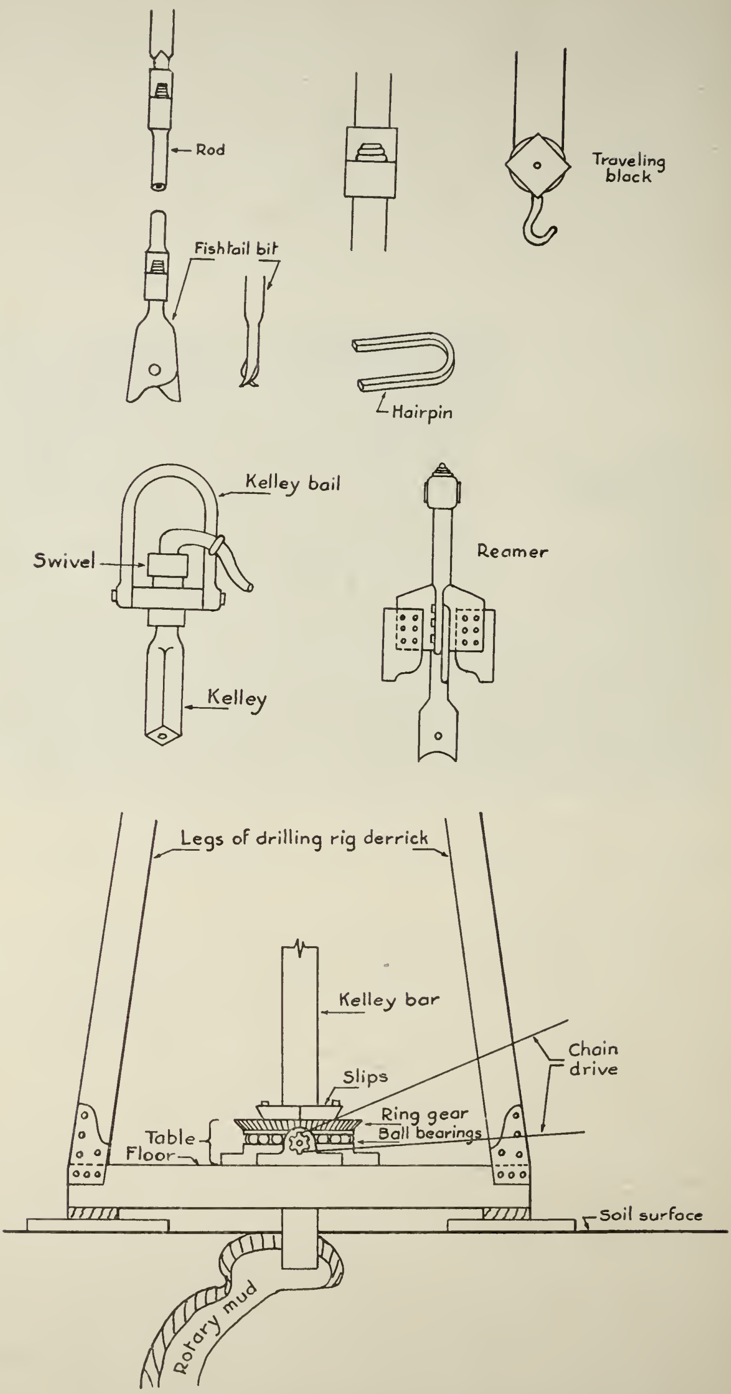

Fig. 13.—Some common rotary-rig tools.

being finished, there should be enough additional gravel to keep the hole full at all times. Figure 14 shows details of a typical gravel-envelope well.

This type of drilling encounters difficulties when the subsurface structures are deficient in clays: the rotary mud produced is not sufficient to fill the hole with the necessary thick suspension. When this happens, the driller must mix

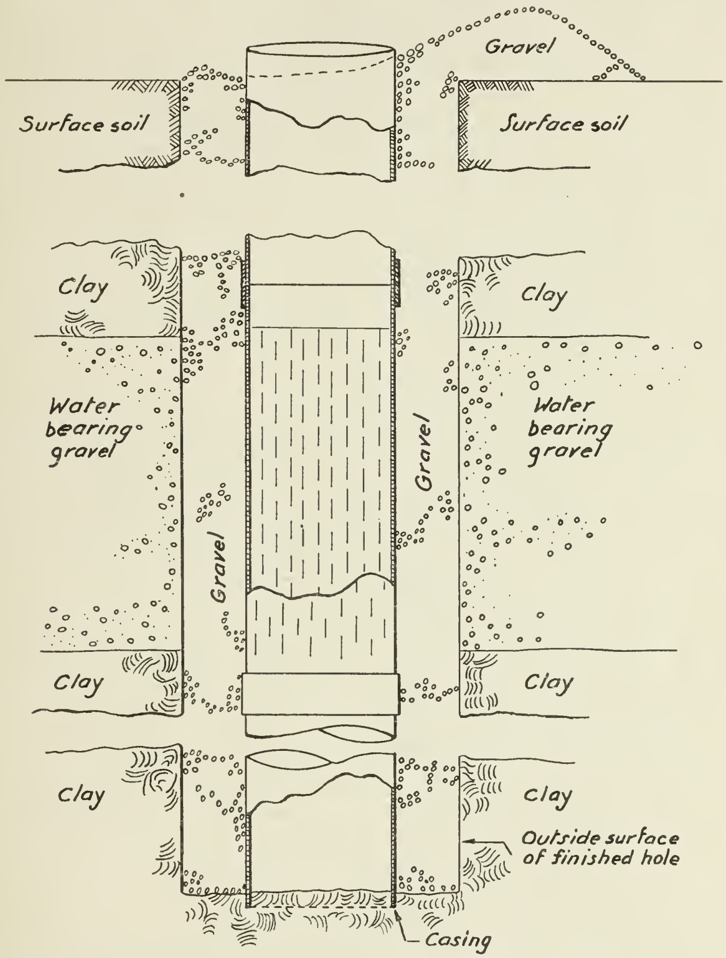

Fig. 14.—Typical section of rotary-drilled well, with gravel envelope and casing in place.

extra clay till the fluid has the desired density. Sometimes porous strata will drain away nearly all the mud before they seal off, and new clay must be worked up to bring the circulation back to the top of the hole. Rotary-drilled wells can be made very large—20 to 30 inches in diameter. This ample size, with the accompanying large area of contact with the porous water-bearing strata, is what commends them. There may be hazards in using the rotary mud, which may permanently seal off some water-bearing strata; but the yields of these wells indicate a beneficial effect from their size.

One possible disadvantage in the porous gravel envelope is that shallow-level impure water can contaminate the main well supply by seeping into the envelope and through it to the water-bearing zone. For large domestic wells the driller can eliminate this hazard by using a special concrete or metal lining outside the gravel for the depth of potential pollution, with a cemented joint between this lining and the inner well casing.

Jetting.—This minor drilling method employs the erosive action of a stream of water to cut a hole. The direction of the cut is controlled by the pointing of the stream in a downward course. Little control over the shape of the hole is possible. One system employs a combination of jetting and boring. The high-velocity stream washes the earth away (as the casing is lowered in the deepening hole) and carries the cuttings up out of the well. Such a jet may cut or scour irregularly, swirling out first one way then another, so that the casing fits the cut volume poorly. Since the use of the jet presupposes a considerable supply of water at the well side, only small-diameter holes (1½ to 3 inches) are normally dug in this way, and then to rather shallow depths. Such wells are suitable for only the most limited irrigation use, because of their small water yield.

WELL LOGS

The well log (fig. 15) is the recorded description of the materials encountered in sequence throughout the drilling, with formations accurately noted as distances from the surface of the ground. All three drilling methods provide a good record of the stratification below the surface. With the exception of the rotary-drilling and jetting, all the methods, as part of the drilling, bring up samples of the immediate formation being cut. This permits inspection and classification while depth is being ascertained by frequent measurement. Since the driller is able to inspect and classify the cuttings frequently, he has a good record of the materials to be found below the rig. He cannot depend, however, solely on the observation of cuttings for his log. He must be constantly alert to the sounds and behavior of tools and rig, which give him the exact location of the change from one material to another. This ability to interpret the structure being cut, through the sound of the rig and the behavior of the tools, comes with practice. In general the rig is heard to labor harder in clay than in other kinds of material. The tools move down readily in sand or gravel, and—by a trained ear—the gravel particles can be heard rattling.

With the rotary-drilling rig, the operator's ability to detect the changes in structure by the behavior of the rig is fundamental to an accurate log. This responsibility falls upon the rotary driller: the samples he does get from the bottom are mixed in the rotary mud stream; and in holes a hundred feet deep or more, the cuttings may not reach the surface till many minutes after the bit has passed a given structure. Fortunately, the rotary-drill bit with its comparatively high speed of rotation affords a continuous audible record of the materials being cut. Clays slow the downward progress, cause the rig to labor, and may at times seize or bind the bit, causing jerky rotative action. Sands and gravels offer little resistance to downward movement of the bit; and large stones or boulders, when encountered, create explosive shocks to the whole drilling outfit until the object has been shoved aside or broken down.

Gravel gives the drilling system a distinct rattle, easily detected with a little practice. The coarser the gravel, the louder the rattle from its contact with the bit.

By observing these indicators and recording the depth at which each change presents itself, the rotary driller obtains an accurate log of the materials and

Fig. 15.—Typical well-driller's notes, with well log plotted to scale from them.

their position below the surface of the ground. True, he has no accurate sample of the material being entered with each change; but this shortcoming is not important: since a water-producing well is the desired result, the colors and similar details of the strata cut are not fundamental.

STRAIGHTNESS OF HOLE

Regardless of the drilling method, the resultant well should be as nearly perpendicular as possible. This requirement must be met so that the pumping equipment can be inserted or withdrawn without becoming stuck, and so that

the shafting and bearings may not be subject to excessive stresses due to bending. The driller should start the first 20 to 40 feet very carefully to see that the hole is absolutely vertical; thus he secures a guide for the remainder. If careless or hurried, he may allow the tools to wander sideways even to the point where the lower part is drilled on a slant rather than in a vertical line. The owner would be justified in refusing payment for such a well if the condition can be discerned in time. On the other hand, curvature at a distance below the lowest possible setting of pumping equipment is not necessarily disastrous and need not prohibit the acceptance of a well.

A vertical hole should be construed as one having vertical sides and a continuously maintained true diameter. If the drilling tool wobbles, the resultant hole may be shaped somewhat like a corkscrew; the diameter of the bore may be too constricted in some sections, too great in others. If the driller is not careful, this condition can occur with any of the tools in use today. The casing will not readily pass poorly trimmed holes. Clay is more apt to present this problem than other materials, although large boulders can create a similar effect by shifting the hole sideways. In the rotary-drilling, where the clean finished diameter depends upon the radius of the cutting edges of the reamers, these edges if worn must be rebuilt to dimension. Otherwise, the resulting hole will be tapered, becoming smaller as drilling progresses. This condition defeats the purpose of the reamers, which are expected to finish a clean cylindrical bore for insertion of the casing and for jacketing of the latter by the gravel envelope. Sometimes, with a gravel envelope, the hole is clean and vertical, but the gravel lodges somewhere on one side of the casing, forcing it out of plumb in that vicinity. As a rule, reasonable care in the running in of the gravel will eliminate this hazard. The owner should expect the driller to finish a well whose casing is plumb at least for the distance to be occupied by pump and column. Any type of equipment described will, if properly used, satisfy this condition.

One can check the alignment of a finished well casing by lowing a "cage"—that is, a piece of pipe which just passes the inside of the casing; or a wooden frame made on the job to the needed dimensions, but slightly smaller than the inside of the casing. The cage must be heavy enough to sink if the casing is full of water; and it is suspended from a strong fine wire attached to the exact center of its top. As the cage is lowered to measured desired depths it is halted, and the suspending wire is caused to pass through the center of the top of the casing while hanging from a point 5 or 10 feet above it. As long as the suspending wire remains vertical while passing through the center of the top of the casing, the cage is vertically below that top. If the cage is off the vertical, the suspending point can be moved to the side to bring the wire into a vertical position; the displacement of the wire (fig. 16) from the top center position is the misalignment of the casing at that depth. When the misalignment equals or exceeds a half diameter, the vertical wire will contact the side of the casing at the top, and no further check of plumbness will be possible with the plumb line or wire alone.

The wire can be moved at the suspending point so it does pass through the center line of the casing at the top of the well. In this position it lines up with the sides of the casing; and if the latter is out of plumb or is off the true ver-

tical line, the wire is also. If 10 feet of the suspending wire is found to be ½ inch out of plumb, the casing is misaligned ½ inch per ten feet of its length down to the top of the cage. In other words, if the cage is down 60 feet in the well and the suspending wire is out of plumb ½ inch per 10 feet of length, the casing is out of plumb $\frac{60}{10} \times \frac{1}{2}$ inch $= 3$ inches at the 60-foot depth. A good spirit level or an independent plumb line can be used to check the deviation of the suspending wire from the true vertical.

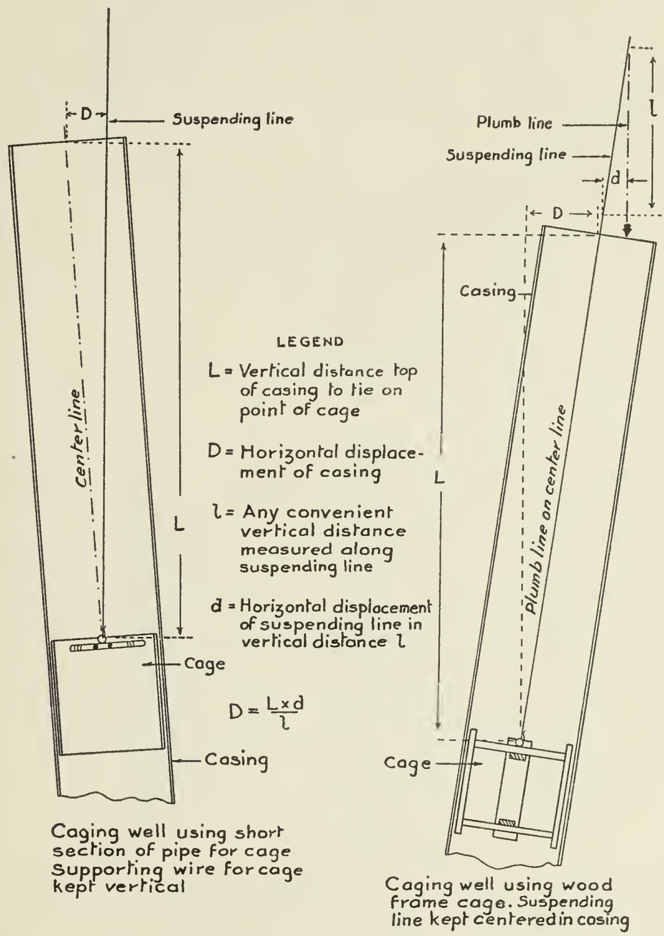

Fig. 16.—Use of cage in well to determine misalignment.

WELL CASING OR LINING

Well casing is the lining that restrains the earthen walls, preventing a cave-in and holding out loose materials. The terms lining and casing, though interchangeable, have each become associated with special materials. Lining or liners are the wood, concrete, or metallic walls installed in wells of large diameter. Casing is the metallic tubing inserted in smaller wells. This iron tubing

may be standard pipe or special fabricated pieces varying in length from 2 to 30 or 40 feet. Large wells might be classified as from 30 inches in diameter, upward. The wood with which they are usually lined is held fast against the excavation by heavy open timber framing (figs. 17 and 18) placed hori-

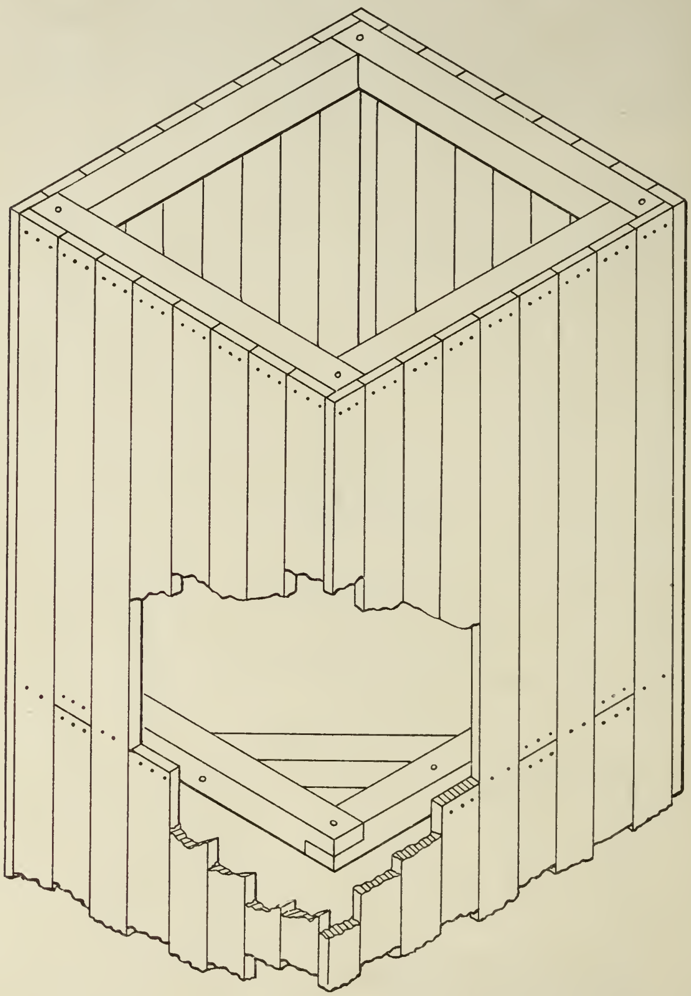

Fig. 17.—Detail of wood-framed well cribbing, showing the breaking of joints on the vertical planks, and the strong inner bracing.

zontally, with the planks that form the lining proper standing vertically outside the frames. The frames may have circular or rectangular outer faces, but occasionally have other shapes—equilateral hexagon or octagon. (See figure 17 for detail of rectangular section wood lining or cribbing.)

Regardless of the shape, these framed internal braces must be carefully laid out and accurately fashioned of strong material; then they can retain their uniform dimensions and shape as the well is dug. While the lining, or cribbing, is moving down following the excavation (added to from the top),

severe strains are set up; and if the frames lose their shape, the vertical planking will be forced out of line and will bind on the earth walls, hindering the downward progress of the lining. In addition, a deformed section will not resist cave-ins so effectively as one that keeps its symmetry. Water enters

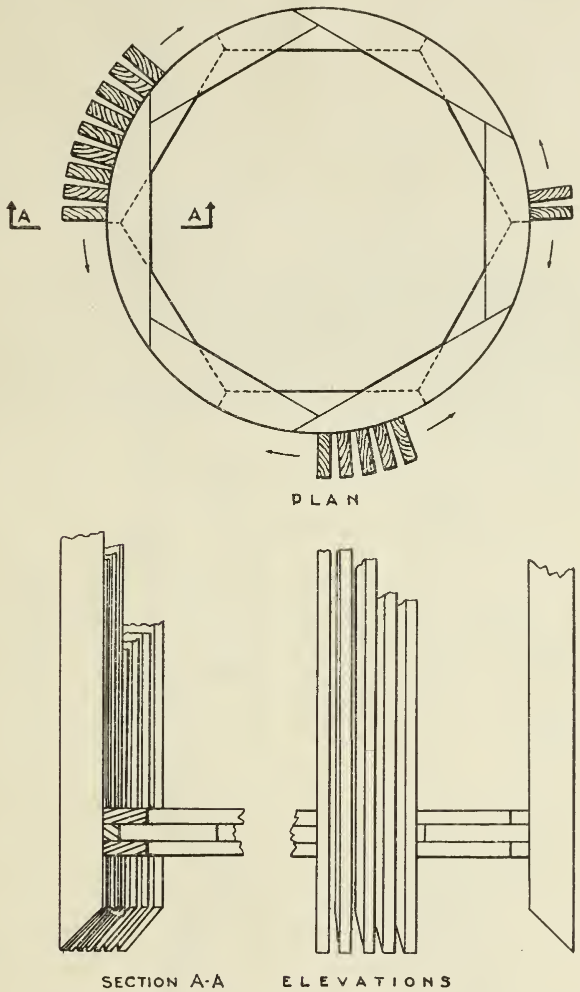

Fig. 18.—Special cylindrical wood cribbing with planking mounted on edge, facing outward, to make slotted wall for entrance of water.

wood-lined wells through slots or bored holes cut in the planking of the walls or through cracks between planks. In some instances (fig. 18), lower sections that will be stopped in a water-bearing stratum, are made up especially to form a vertically slotted wooden screen; the planking is placed with the edge face outward, and open joints are left between planks.

Large-diameter concrete pipes (fig. 19) are used occasionally for the larger wells. With these, new sections are placed on the top as the lower sections settle

down immediately after the excavation. A continuous concrete lining can be made by pouring the concrete within forms at the top as the excavation proceeds, allowing the growing cured section to follow the excavation. Under this plan one can have steel reinforcing throughout the concrete well lining, mak-

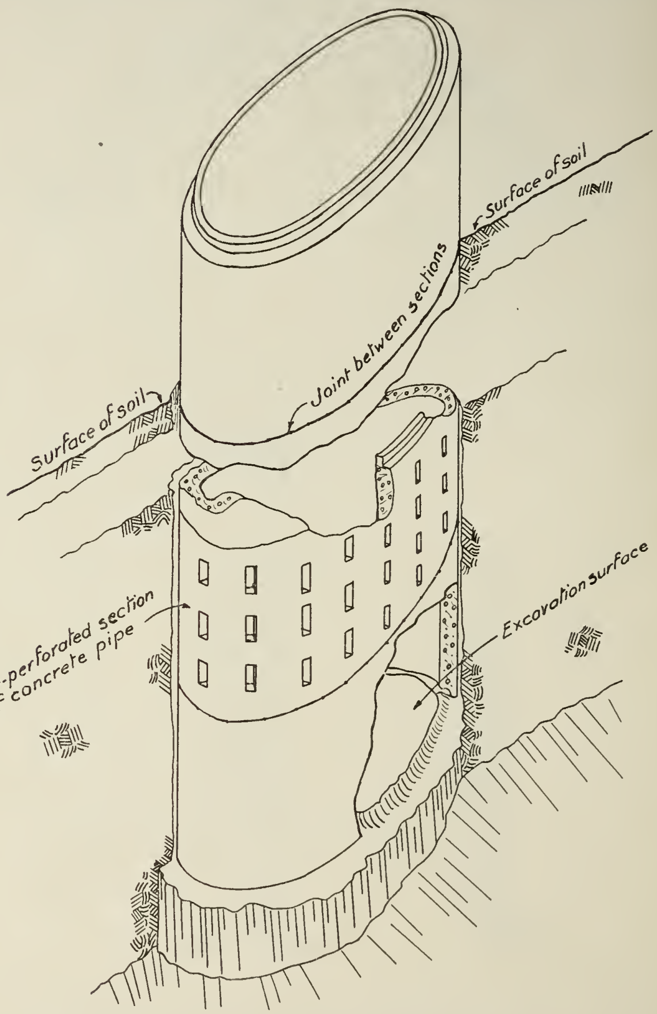

Fig. 19.—Large-diameter concrete pipe used as well lining, including perforated sections.

ing the finished liner a homogeneous unit. Perforations for concrete walls must be cast at the time the concrete is poured. The cores for the perforations may be wood, clay, or soft brick that can be removed after the cement has set. All perforations should be wider toward the inside wall of the liner; in a given opening they should be long and narrow rather than square or round. The long, narrow opening admits only the smaller particles of gravel while presenting, at the same time, a large area of opening for the entrance of the

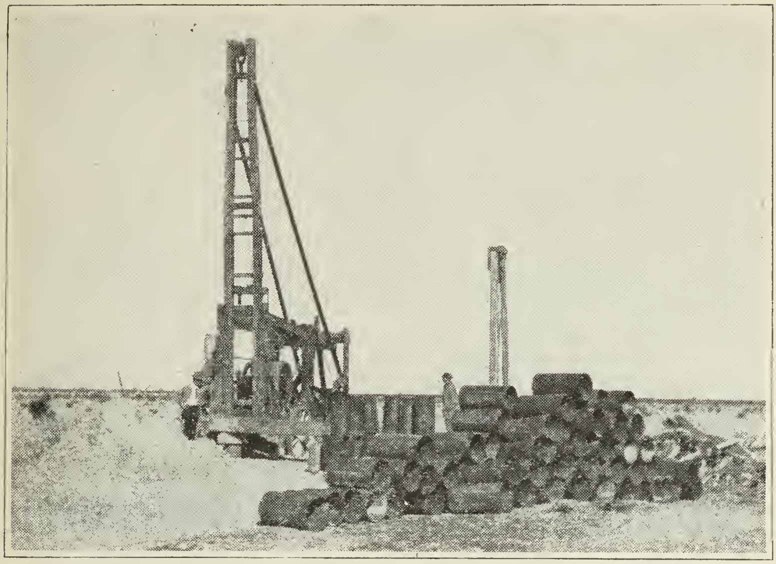

Fig. 20.—Two sizes of stovepipe casing piled separately, in front of cable-tool rig.

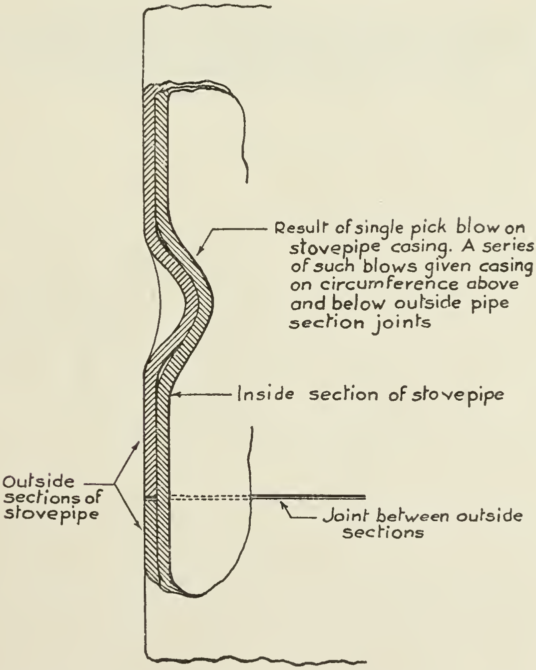

Fig. 21.—Detail of "picked" joint of stovepipe casing.

water. Because of the wider section toward the inside, particles that do get past the entrance section are prevented from accumulating in the passageway and blocking the flow. The entrance opening can be an inch wide if the gravel to be excluded is larger than 1 inch.

Casing as defined includes a wide range of materials, varying from light-

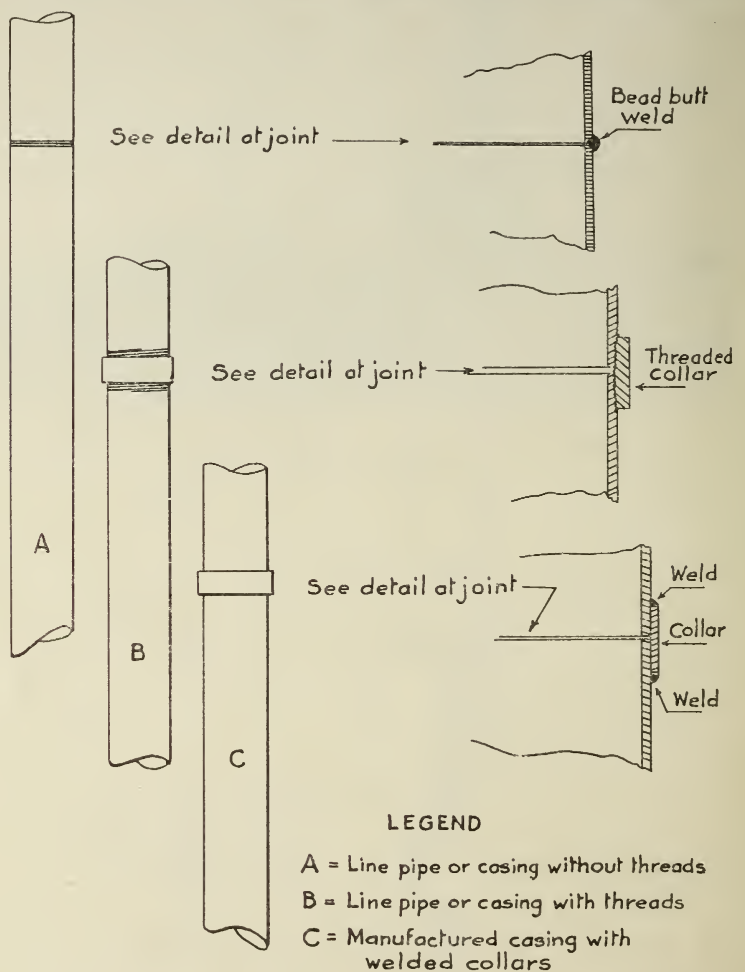

Fig. 22.—Detail of three types of casing and the corresponding joints.

weight galvanized sheet-metal tubes to standard line pipe. Lighter-weight materials are used on wells less than approximately 10 inches in diameter. The heavier casing is required in the larger holes to resist collapse under the load of the caving sides. The light-weight casings, being shorter-lived than the heavier ones, are not recommended for irrigation wells. One exception is the so-called stovepipe casing. This is made up of laminated layers formed by telescoping one cylindrical section halfway through another (fig. 20), so that light, easily handled, 30-inch lengths are assembled to make a continuous

pipe of two or more thicknesses with all joints staggered. The sections are fastened together by hitting them forcibly with a sharp tool such as the point of a pick. The resultant dent in the outer shell seats in a corresponding dent in the inside sheet (fig. 21). Four to a dozen of these dents per section join the sections sufficiently to permit pulling of the casing if need be. Without the dents, the sections would pull apart from their own weight during installation. Casing is seldom made up at the well; most of it is prepared in special shops. Stovepipe casing is occasionally made up ready to roll into cylindrical form,

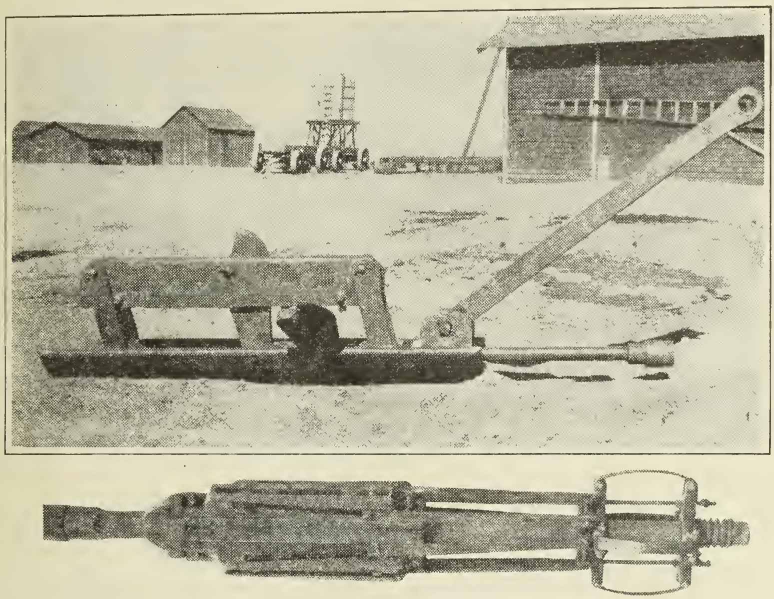

Fig. 23.—Single-blade (upper) and multiblade (lower) casing-perforating tools.

with all rivet holes punched, and is then shipped flat to save space if it must be transported a considerable distance.

Heavier casing is made from heavy flat sheets that are cut to exact width, then rolled at the shop into cylindrical form in 20-foot lengths. The edges of the sheet are welded, completing the cylinder. A collar of the same weight metal is welded around one end of each of these cylinders so that half the collar is on the cylinder and the other half extends beyond. At the well (fig. 22) the uncollared end of each cylinder seats into the collared end of the one below, and the newly inserted cylinder is welded to the collar in which it rests. In this way the continuous casing is assembled on the job.

Light-weight pipe, called casing pipe, and standard line pipe have threaded collars or couplings for joining the separate lengths. The casing thread is finer than standard pipe thread; and casing dimensions refer to outside sizes, whereas pipe dimensions are for inside. Both these forms of casing can be purchased without threads and then welded together on the job, section by section, as the casing is lowered.

Regardless of the material used in well casing, provision must be made for water to enter through its walls in the vicinity of the water-bearing strata. The well log gives the location of these strata; but if the casing has been inserted as drilling progresses, no information may have been available to show where the perforations or entrances should be. In that case the perforating must be done on the job. Many tools (fig. 23) are available for this purpose.

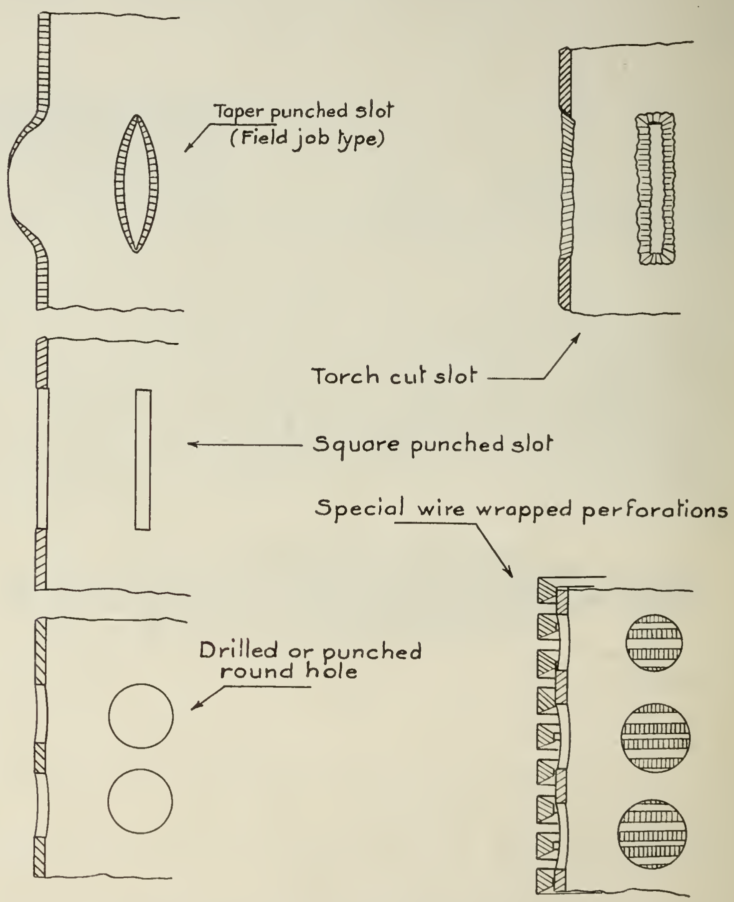

Fig. 24.—Details of several types of perforations and one type of screen.

Each has one or more knives that are forced outward and through the casing under the control of the well driller. The latter tries to obtain a regular pattern of these cuts or slots in the zone required, but cannot always be certain of accuracy until the well is put to test. If he knows the location of water-bearing zones, he can buy the casing perforated in the lengths required and, by inserting it correctly, can make it match the water-bearing layers. Rotary-drilled wells give adequate opportunity to match water-bearing strata and casing perforations: the log can be ascertained before the casing is ordered, and records from the pilot hole can be used.

Shop-made perforations (fig. 24) are formed under perfect control and can be put in on even spacing with precision. This control insures that the casing will not be weakened by the perforation job. The knife in the field job makes a tapered hole with the wide face inside, and any good shop-perforated casing is made with similarly tapered holes or slots. The shop-made perforation may be punched, chiseled, or torch cut, and is normally cleaner than the perforations made in the field after the casing is in the well. In some areas where fine sand is present in the water-bearing formations, the perforations must be screened; the perforated casing is wrapped with specially formed wire to give a fine, narrow, spiral opening through which the sand cannot pass. Such wrapped casing is factory-made. The precaution is not necessary in most California wells.

WELL DEVELOPMENT

A well should not be considered finished when the casing, with the necessary perforations, is installed. It should undergo a development test to serve three objectives. First, this test proves whether a water supply has actually been found; second, it removes the sand and other foreign matter about the well casing so that only clear water is pumped; and third, it supplies a set of data to portray the characteristics of the well. From these data can be determined the size of pump to be used or the amount that a given pump can draw.

The main purpose of the test is, of course, the same as in drilling any well—namely, a water supply. The test provides the first proof of success of failure; and this proof is attained automatically along with the second objective—the elimination of suspended matter from the water. Data necessary to the third objective also result from successful cleaning of the well.

All of the porous materials that form the water-conducting strata tapped contain fine particles that will move toward the well when water is being withdrawn from the casing by pumping. In the rotary-drilled well, the rotary mud has flooded these strata to some extent. All drilling procedures mix more or less foreign material into the facing of these porous zones. These finer and foreign materials seal the pores of the water-producing strata; and when they are washed out, the delivery of water to the well is facilitated. The procedure then is to create a circulation in the water-producing zones that will loosen the material to be removed. For this purpose, the drilling equipment provides preliminary tools. The bailer (fig. 9) will bucket out the water and clean sediment from the bottom of the hole. (Rotary rigs, too, usually have lines for the operation of a bailer.) Each bailerful removed permits the entrance of an equivalent volume of water from the water-producing zones. This causes motion into the well, and the moving water carries the loose material with it. If the bailer is allowed to descend rapidly, the counter current resulting will force water outward and loosen more trash, which will follow the inward-bound current when the bailer is elevated. Rapid elevation causes a heavier surge inward, bringing in more material. The intensity of the surging is stepped up from gentle to strenuous activity as the work progresses.

By putting a jacket of canvas belting or rope about the bailer, one can make the casing fit rather tightly; when lowered and raised it acts as a piston, forcing water before it. Similar pistons (fig. 25) are sometimes made of wood or other materials for the same purpose. The energetic operation of pistonlike

equipment causes surges in the water-bearing zones about the casing, and through this disturbance the fine sediments are moved into the well. Their movement usually ceases after the piston has operated for a while, and the development of the well by this means is complete, within the limitations of the method.

One can keep a time record of the number of bailerfuls of water removed from the well and check the corresponding lowering from the static water

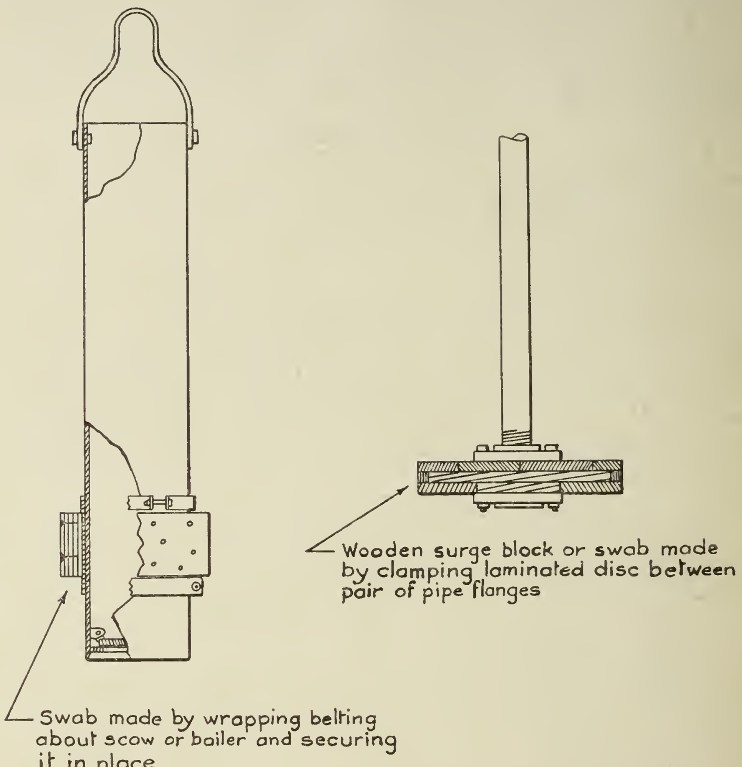

Fig. 25.—Swab and surge-block details.

level. Since the bailer has a known volume, the number of bailerfuls per unit of time gives the discharge rate of the well. Corresponding to this rate will be a given measurement of the depth to water, which will prove to be greater than the depth to the water surface when no water has been removed for a while. This lowering of the surface by the bailer is called the drawdown. For one rate of flow it will prove to be equal to half the drawdown for twice that flow, or proportional to the rate of discharge. Since this well characteristic is almost universal in California, where artesian-type wells are the rule, one can safely apply the formula up to the point where the first water-bearing stratum begins to be uncovered. At this point, the perforated area of entrance for the incoming supply is reduced; and thereafter the drawdown progresses more rapidly with increased demand than has been the rule.

Since the operation of the bailer permits only a limited draught on the well, a test or developing pump should be used if possible. There are two reasons: first, the greater demand of the pump upon the water-supplying strata will probably cause, in these zones, increased flow velocities that will bring in more solids; second, this movement of these loosened particles will further open the structure, so that the friction loss due to movement through them becomes less. This lowering of friction losses means reduced drawdown, and the well will be correspondingly improved. If the test pump does not remove these solids, the new pump will have to do so; its critical, carefully machined inner surfaces will become cut and worn. Such wear, although very light, markedly reduces efficiency; irreparable damage results at the beginning of the life of the new unit, and the owner will pay thereafter in larger power costs.

The test pump can do the whole development job in a well, and most drillers can bring in a unit at a nominal charge. As a rule, the pump should be belt driven so that its speed is subject to control. It gives the owner the opportunity to supply his own motive power if he desires. Speed control on the pump is necessary because the demand on the well should be gradually stepped up as the test continues. The test may require 20 or more hours of operating the pump; at the end, the demand on the well should be at least equal to the desired discharge or, better, as much as $1\frac{1}{2}$ times the desired flow. If the demand is made as great as possible, the largest volume of loose material will be cleaned away from the water strata, and only clear water will pass through the new unit. Stopping and starting the pump during the test will cause surges to wash away any loose material near the perforated casing, sweeping it into the well. This surging is important; with clear water the ultimate goal, the well is not fully developed till the surge ceases to produce large new quantities of solids.

A direct-connected, electric-motor-driven well-test pump is satisfactory for use in developing a new well if a discharge valve is supplied. Under this arrangement, one can step up the flow from the well gradually by opening the discharge valve a little at a time, running the pump for a reasonable period before each change in setting the valve. Surging is accomplished by stopping and starting the motor by use of the electric switch.

If the discharge and depth to water in the well are recorded during the test, the drawdown for a given discharge rate is found to be much greater at first than toward the end. This is proof that the water-bearing strata have been flushed of their obstruction.

Sometimes the developing pump draws in solids from without the casing and deposits them at the bottom of the hole. To eliminate this condition, the suction pipe of the pump is extended to the lower part of the well so that no volume of quiet water is left for settlement of the suspended load. If it proves impracticable to extend the suction pipe to the full depth of the well, the bottom must be cleaned with a bailer, sometimes during the test and necessarily afterward. Though one must remove the pump in order to bail, such procedure is sometimes necessary in order that all possible strata may be developed as completely as possible and the maximum yield obtained, with the minimum drawdown.

DEPTH-TO-WATER MEASUREMENTS

A stout piece of cord or a marked tape may be used for measuring the depth to water in the open hole. When, however, the pump is in the well, there is not much space between pump and casing; tapes and plumb lines become wet by contact with pipe and casing; and accurate reading is impossible. In that event, electrical contacts or air lines replace these devices (fig. 26).

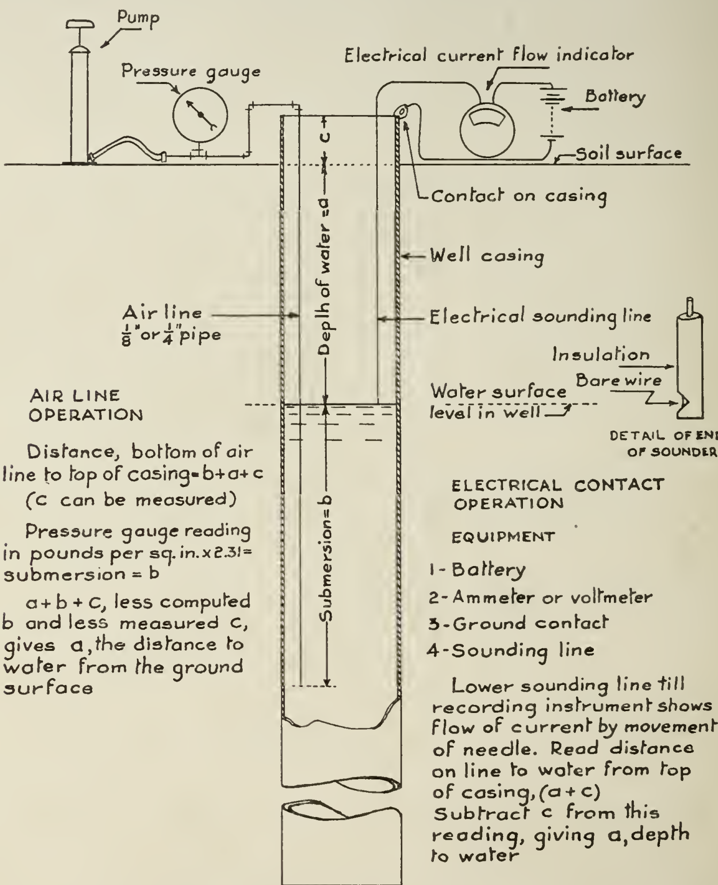

Fig. 26.—Devices for measuring depth to water.

The electrical contact is made by means of an insulated wire with a shielded contact which is small enough to go through constricted passages, but which will ground or complete a circuit in the free water. When contact with the water is made, a bell rings steadily, or an ammeter shows that a current is flowing. The exact position of the water can be scaled directly on the line or by removing the line from the well and checking the distance upon it with a tape. Fastening a few feet of fish line to the end of the scunding wire and stringing small weights on this line will materially assist the use of the sounder because the weights act as guides feeding the wire past constricted places.

Another sounding device is the airline. This is a small-diameter pipe (¼ or ⅛ inch), usually galvanized iron (but preferably copper for long life), run down at least 10 feet below the lowest pumping depth of water in the well. The exact length of this pipe is recorded; then a pressure gauge and an air pump are connected to the upper end. When air is forced into the pipe, the pressure builds up inside till air begins to bubble out of the bottom of the pipe. Thereafter, no more pressure can be built up; the accumulated pressure now equals the depth of submergence of the pipe. If the gauge reads in pounds per square inch, the submergence in feet equals that reading times 2.31. The depth to water equals the distance from the ground surface to the bottom of the pipe minus the submergence. Some air-line pressure gauges are marked in feet so that the depth to water is read directly on the gauge itself.

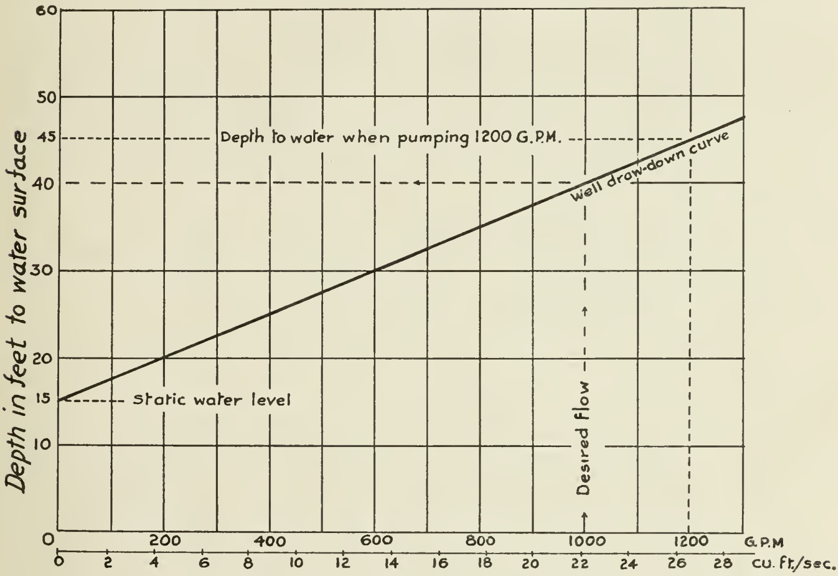

Fig. 27.—Drawdown curve for well. (See discussion in text, page 34.)

USE OF WELL DRAWDOWN IN SELECTING A PUMP

The drawdown characteristics of the well have been emphasized here because these data have great value in the selection of a pump to fit. If the water in a well stands at an elevation only 5 feet below the top of the casing before pumping begins, it might be thought to be within reach of a pump situated at the top of the casing. This is not likely, however, because the water level will recede as soon as the pump is started. Any type of pump operates less efficiently as the suction lift increases. The maximum suction lift theoretically possible, but not actually attainable, is just under 34 feet. The centrifugal-type pump suffers more from increasing suction lift than positive displacement forms of pump; and the centrifugal type, capable of large discharge rates, is most frequently used for irrigation purposes. To avoid the possibility of excessive suction lift, this type of pump is installed in special designs, called deep-well turbines, that suspend the pump proper down inside the well casing

10 or 20 feet below the lowest water level after the drawdown is complete. The drive shaft for such pumps extends to the top of the ground inside the discharge pipe, and power is applied at the top. Information regarding standing water levels and the pumping water levels is fundamental to the proper application of most irrigation pumps to the well.

The following figures might be available at the conclusion of a development run:

1. Flow or discharge . . . . 1,200 gallons per minute (clear water)
2. Depth to water while pumping at this rate . . . . 45 feet
3. Depth to water 30 minutes or more after the pump stopped (static water level) . . . . 15 feet
4. Drawdown for 1,200 gallons per minute . . . . 30 feet (*2* minus *3*)
5. Desired pump capacity . . . . 1,000 gallons per minute (required for crop)

One can either lay out these items on a chart or graph and picture the conditions, or calculate a solution. The graph is the more enlightening and will be more useful in selecting the pump. Figure 27 illustrates conditions for the tabulation above. For a discharge of 1,000 gallons per minute, the depth to water will be 40 feet. This value could have been determined by the following simple calculation:

Drawdown for 1,200 gallons per minute = 30 feet.

Discharge (gallons per minute per foot drawdown) $= \frac{1200}{30} = 40$ gallons per minute per foot drawdown.

Drawdown for 1,000 gallons per minute $= \frac{1000}{40} = 25$ feet.

Static water level plus drawdown (total depth to water) = 15 feet + 25 feet = 40 feet.

A pump capable of lifting 1,000 gallons per minute 40 feet is required if the desired flow is to be obtained at the surface of the ground. If the water must be discharged through a pipe line for any distance, the pump must overcome additional lift because of friction loss plus any change in elevation (plus for a rise, minus for a drop). In the simplest case, where the pump lifts the water out of the well only (1,000 gallons per minute, at a 40-foot lift), bids might be obtained from vendors who have been asked to supply the head-capacity curves for each pump bid upon. These curves, or the data from which they are drawn, can be plotted on a drawdown graph for the well, the same scale being used for the pump curves as for the drawdown line.

Figure 28 illustrates the result of graphing typical pump data from three bidders. The curve for pump 1 intersects the drawdown curve at exactly 1,000 gallons per minute and 40 feet, and the unit is satisfactory so long as the total lift for this flow remains constant. Part of the time, the pump may deliver 1,000 gallons per minute through a pipe line or to an elevation that adds, say, 10 feet more lift. The total lift then becomes 40 feet plus 10 feet equals 50 feet, and pump 2 is the most satisfactory if no less than 1,000 gallons per minute must be supplied. If pump 2 is used and if the discharge is released at the surface of the ground, the flow will become a little over 1,140 gallons per minute.

There might not be two discharge conditions to be met; but if the water

levels in the well were lowered, during the season, a total of 10 feet (as is quite possible anywhere in the state), the static water level would then be 10 feet lower, and the drawdown curve would be shifted upward 10 feet all the way. The effect on figure 28 is to raise the drawdown curve to the position of line *a*. With this shift in water levels, pump 2 fits the requirements for the minimum 1,000 gallons per minute flow. If pump 1 were put in the well and the water levels dropped the 10 feet, the discharge would become about 830 gallons per minute.

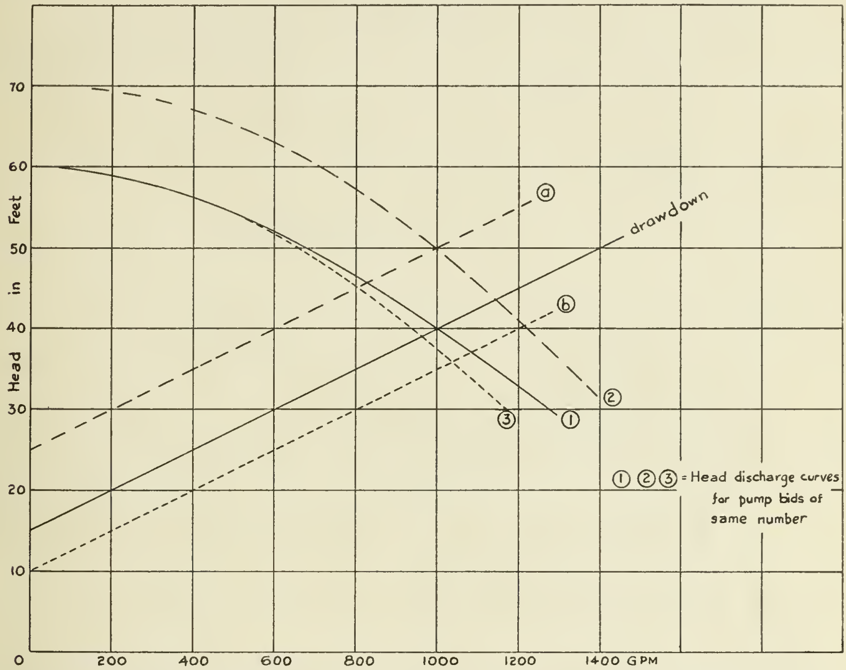

Fig. 28.—Use of drawdown curve and pump-head discharge curves on same chart in selecting most satisfactory pump to fit conditions.

Conceivably, the well test might have been made when water levels were down as far as could be expected, and they would therefore average 5 feet higher most of the pumping season. On this basis the average drawdown curve would be shifted downward 5 feet to *b*. Under these conditions, pump 3 might be satisfactory: it would deliver 1,040 gallons per minute most of the season, and not less than 970 during the short remaining period. Under this last assumption, there might be a choice between pumps 1 and 3, the purchase depending upon expected service, or upon efficiency of operation, or both.

Every well or area has its own drawdown characteristics and can be efficiently fitted with a pump only if one considers them. For the well in the discussion, several typical possibilities have been suggested to illustrate the use of these data in selecting the correct pump. For a proper fit of pump and well, similar figures on the particular well involved must be applied to the pump-performance data available. A pump that has slightly more capacity than required is a better investment than one that just meets the requirements.

THE WELL-DRILLING AGREEMENT

When a prospective well-owner and a driller begin to discuss operations, the owner should have a basis on which to start. For this reason, the following agreement is suggested as a plan by which both parties can indicate their desires and promises. Most drillers are familiar with or have similar forms, and the owner should possess a general knowledge of the text before making final arrangements.

Well-Drilling Agreement

This agreement (signed and dated at the bottom by the driller and the owner) described below, covers the drilling of a water well on the land of the owner, whose property is located.................... miles............................ of the city of.......................................,......................
(Direction) (State)
Owner: ...., whose post-office address is ....
(Name)
Driller: ...., whose post-office address is ....
(Name)
Item:

A. Location of well: ....
(Where and by whom)

B. Drilling method: ...., using driller's equipment.
(Type)

C. Inside diameter and depth of finished hole:*..
....
....

1. Depth of finished well to be decided by owner after completion of pilot or test hole, if rotary-drilled.
2. Cost of pilot hole (if rotary-drilled well): (a)............................ per foot if pilot hole only is drilled, and no charge for pilot hole if well is finished to specified diameter to depth decided upon by owner under item C, 1. (b) If owner decides pilot-hole showing is unfavorable, he may decide not to drill the finished well at that location and shall then reimburse driller for depth of pilot hole drilled at the rate named above and shall be subject to no additional charge for services by the driller for work at that location.
3. Depth of pilot hole, not more than .... feet.

D. Finished hole to be plumb of wall and of true diameter throughout its depth, per item C.

E. Driller will supply owner with accurate log of all materials encountered to depth penetrated, to complete owner's record of well. Driller will, at owner's request, supply owner with samples of all identified gravels encountered and also supply data as to their depth and thickness. If the well is to be rotary-drilled, before its final depths and dimensions can be decided upon, the owner must have these data as supplied by the pilot hole.

F. Casing:

Depth	Inside diameter in inches	Type	Weight or thickness	Type of joints	When and how joints are to be finished
0 to........	....	....	....	....	....
.... to	....	....	....	....	....
.... to	....	....	....	....	....
.... to	....	....	....	....	....

All field joints will be finished to make a tight, continuous tube with inside surface as smooth as possible.

* Give determined dimensions and depths; or arrange for field decision on this item, and for entry in this agreement at that time.

Perforations in casing:

Depth	How made	Number per sq. ft.	Dimensions	Remarks
0 to........				
........to........				
........to........				
........to........				
........to........				

G. Gravel envelope (rotary-drilled wells): (1) To be washed, clean gravel of .... inches graded diameter. (2) At least 3 yards gravel to be left at well when all gravel envelope has been run in.

H. Water supply when drilling (who will supply water for drilling and charges, if any):

....

I. Performance: Driller will take every reasonable precaution to protect owner's property while drilling and will remove his equipment and clean up the working area within .... days after acceptance of the job by the owner. Driller will not have to remove or clean up excavated material from well, but will keep it within reasonable bounds during the drilling operation.

J. Payments:

1. Driller agrees to finish the well described, and in the manner given in the preceding tabulations, complete with the casing, plain and perforated, as decided upon and complete with the gravel envelope (if rotary-drilled), at the cost per unit depth to the owner as follows; and to make no other charge to the owner for the job:

Depth in feet	Casing diameter and type	Cost casing per foot installed	Perforations, cost per foot	Finished hole, diameter, inches	Cost finished hole per foot	Cost gravel envelope if used, per foot
0 to........						
........to........						
........to........						
........to........						
........to........						
........to........						
........to........						
........to........						

2. Owner will pay ....
(Payment procedure)

....

....

K. Development of well. The owner and driller mutually agree: ....

....

....

....

L. Insurance. Driller agrees to insure himself against all claims that may arise from any injury to his crew or himself while on the drilling job and absolves the owner from all responsibility in this matter.

The owner and the driller, having agreed together, and each having accepted as his responsibility that portion of this agreement which becomes his to perform, have placed their signatures on this.............. day of...................., 19...., at......................................

Signed:

...., Owner

...., Driller

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